Restoration Notes

Restoration Notes have been a distinguishing feature of *Ecological Restoration* for more than 25 years. This section is geared toward introducing innovative research, tools, technologies, programs, and ideas, as well as providing short-term research results and updates on ongoing efforts. Please direct submissions and inquiries to the editorial staff (ERjournal@aesop.rutgers.edu).

Roots of Chaparral Shrubs Still Fail to Penetrate a GeoSynthetic Landfill Liner after 16 Years

Karen D. Holl (Department of Environmental Studies at the University of California, Santa Cruz, CA 95064, kholl@ucsc.edu) and Sean McStay (University of California Fort Ord Natural Reserve, Marina, CA 93933).

In the past, legislation in the United States (USEPA 1989) and most of Europe (Forster 1993) restricted the planting of woody shrubs and trees on landfills, largely because regulators feared that roots of woody plants would penetrate the landfill liner (Dobson and Moffat, 1995). This limitation precluded revegetating landfills with pre-disturbance ecosystems, such as chaparral, in which woody species are an important part of the vegetation. More recently, a wider range of species, including shrub and tree species, have been permitted for revegetation on landfills, but root morphology and depth remain major criteria for species selection (Calrecycle 1999; USEPA 2006).

Most previous studies across several temperate ecosystems suggest that tree roots do not penetrate landfill liners (Gillman 1989, Dobson and Moffat 1995, Robinson and Handel 1995, Handel et al. 1997, Hutchings et al. 2001). Moffat et al. (2008), however, found that tree roots in Great Britain occasionally penetrated weaker areas of a mineral landfill liner, particularly when the soil layer over the cap was < 1 m. In an earlier paper, we reported that the roots of 11 species of California coastal chaparral shrubs did not penetrate a geosynthetic landfill liner, but shrubs and trees were only 3–5 years old at the time and growth is notoriously slow in the sandy infertile soils and low rainfall conditions (Holl 2002). Here we provide an update on this study after 16 years in order to provide more conclusive guidance on whether woody chaparral species should be used in landfill revegetation.

In 1997, we established the study at the former Fort Ord Army base in the city of Marina, Monterey County, California. Maritime chaparral in this region is dominated by shrubs, including several species of manzanita (*Arctostaphylos*) and ceanothus (*Ceanothus*), and a high diversity of annual herbs (Griffin 1978). The soils are medium-grained sands (92–96 percent sand) that are well-drained, and have low organic matter content and fertility (Holl 2002). Mean rainfall is 475 mm per year with high interannual variability (275 to 957 mm; National Climate Data Center, Asheville, NC).

We planted eight shrub and one tree species separated by 1.5 m on an experimental area with a 40-mil polyethylene geomembrane liner (Poly-Flex Construction, Inc., Grand Prairie, Texas) covered with approximately 65 cm of soil in order to match regulations at the time. For more experimental design details see Holl (2002). In 2013, 16 years after planting, we used shovels and trowels to excavate 2–3 of the largest individuals of four planted species: chamise (*Adenostema fasciculatum*), sandmat manzanita (*Arctostaphylos pumila*), Monterey ceanothus (*Ceanothus rigida*), and coast live oak (*Quercus agrifolia*). We also excavated three naturally colonizing individuals of Torrey pine (*Pinus torreyana*) (> 4 m in height and > 10 cm diameter at breast height), as well as one particularly large (2 m height, ~10 m² aerial) cover coyote brush (*Baccharis pilularis*) on the landfill liner. All originally-planted coyote brush had senesced. We followed all major roots of each plant until they became 2–3 mm diameter. We also excavated three Torrey pine and one coast live oak tree in maritime chaparral adjacent to the experimental area to compare taproot morphology off the landfill liner.

No roots of any of the six species penetrated the landfill liner, although roots of most species excavated often reached the liner, consistent with our earlier results (Holl 2002). Roots of four of the species, chamise, sandmat manzanita, coyote brush, and Monterey ceanothus usually had a taproot that split into 2–5 medium sized (> 2 cm diameter) roots that primarily spread laterally in the top 30 cm of soil. Occasionally, the roots would grow deeper and run along the liner for up to 4 m. The lateral extent of the excavated roots (> 2–3 mm diameter) was generally only 1–2 m longer than earlier excavations (Table 1, Holl 2002).

Both Torrey pine and coast live oak have thick taproots; for example in Torrey pine the main taproot of all individuals was 8–10 cm diameter immediately below the soil surface. On the liner, the taproots of both species abruptly turned laterally ~20–40 cm below the soil surface (Figure 1) and split into several smaller roots which

Ecological Restoration Vol. 32, No. 2, 2014
ISSN 1522-4740 E-ISSN 1543-4079

Table 1. Results of excavations of chaparral shrubs and trees on landfill liner.

Species	Number excavated	Max. root depth[a] (m)	Max. lateral root spread (m)
chamise (*Adenostema fasciculatum*)	2	liner	3.0
sandmat manzanita (*Arctostaphylos pumila*)	2	0.6	4.5
coyote brush[b] (*Baccharis pilularis*)	1	liner	5.0
Monterey ceanothus (*Ceanothus rigidus*)	3	liner	5.3
Torrey pine[b] (*Pinus torreyana*)	3	liner	> 7.0
coast live oak (*Quercus agrifolia*)	2	0.4	3.2

[a]The liner was at 0.65–0.70 m depth on the test cap.
[b]Naturally colonizing species.

occasionally reached, but did not penetrate, the liner. Off the experimental area, the tap roots grew straight down (Figure 1) and were all > 7 cm diameter at 65 cm depth (a comparable depth to the liner). Our prior excavations of shrubs off the landfill cap (Holl 2002), as well as published information (Hellmers 1955, Kummerow et al. 1977, Kummerow and Mangan 1981), suggest that most chaparral shrub roots grow at less than 60 cm depths, but that taproots of some chaparral species can extend well beyond the 60–70 cm depth of the liner when grown in deeper soils.

Differences in root morphology on landfills versus deeper soils are common and may affect growth (Handel et al. 1997, Holl 2002). Chaparral soils have highly variable depths to base rock (Kummerow et al. 1977) so it is not surprising that chaparral species have evolved a variable root morphology. One caveat is that the growth rate on this site is clearly nutrient limited (Holl 2002) and, therefore, studies are needed on more fertile soils, as coastal chaparral is found across a range from low to medium fertility (Callaway and Davis 1993, Vasey 2012).

Figure 1. Taproot of ~15–cm diameter Torrey pine (*Pinus torreyana*) trees growing on (left) and off (right) a landfill liner. Note that the taproot of the tree on the liner turns abruptly left and splits into several smaller roots, whereas the taproot of the tree growing off the liner is straight.

Our results demonstrate that a number of species of chaparral shrubs are able to survive and grow on landfills without constituting a threat to the integrity of a 40-mil geosynthetic landfill liner and, therefore, do not need to be excluded from landfill revegetation efforts nor removed when naturally colonizing landfill sites. This result agrees with most previous research on landfills suggesting that woody plant roots rarely penetrate intact liners and that woody plant roots have fairly plastic morphology allowing them to adjust to their immediate microenvironment (Handel et al. 1997, Parsons et al. 1998). The 60–70 cm soil layer used in our study was sufficient for chaparral shrub roots, but greater depths of soil overlaying the liner may be needed for forested systems (Moffatt et al. 2008).

Acknowledgments

The U.S. Army Corps of Engineers and the National Defense Center for Environmental Excellence provided funding for the set-up of this study. We thank Gage Dayton and several UCSC students for assistance with logistics and excavations.

References

Callaway, R.M. and F.W. Davis. 1993. Vegetation dynamics, fire, and the physical-environment in coastal central California. *Ecology* 74:1567–1578.

Calrecycle. 2009. A guide to the revegetation and environmental restoration of closed landfills. www.calrecycle.ca.gov/SWFacilities/Closure/Revegetate/.

Dobson, M.C. and A.J. Moffat. 1995. A re-evaluation of objections to tree planting on containment landfills. *Waste Management and Research* 13:579–600.

Forster, A. 1993. Landfill capping review. An assessment of current practices and performance within the United Kingdom, the rest of Europe and the United States. Department of the Environment Contract Report No. PECD 7/10/251. London: United Kingdom.

Gillman, E.F. 1989. Tree root depth relative to landfill tolerance. *HortScience* 24:857.

Griffin J.R. 1978. Maritime chaparral and endemic shrubs of the Monterey Bay Region. *Madrono* 25:65–112.

Handel, S.N, G.R. Robinson, F.J. William and J.H. Mattei. 1997. Restoration of woody plants to capped landfills. *Restoration Ecology* 5:178–186.
Hellmers, H., J.S. Horton, G. Juhren and J. O'Keefe. 1955. Root systems of some chaparral plants in southern California. *Ecology* 36: 67–678.
Holl, K.D. 2002. Roots of chaparral shrubs fail to penetrate a geosynthetic landfill liner. *Ecological Restoration* 20:111–115.
Hutchings, T.R., A.J. Moffat and R.A. Kemp. 2001. Effects of rooting and tree growth of selected woodland species on cap integrity in a mineral capped landfill site. *Waste Management & Research* 19:194–200.
Kummerow, J., D. Krause and W. Jow. 1977. Root systems of chaparral shrubs. *Oecologia* 29:163–177.
Kummerow, J. and R. Mangan. 1981. Root systems in *Quercus dumosa* Nutt. dominated chaparral in southern California. *Acta Oecologica* 2:177–188.
Moffat, A. J., D. Sinnett and T.R. Hutchings. 2008. Containment landfill sites–how to restore to beneficial land-use without compromising pollution control systems. *Chemical Hazards and Poisons Report* 13:37–39.
Parsons, W.F.J., J.G. Ehrenfeld and S.N. Handel. 1998. Vertical growth and mycorrhizal infection of woody plant roots as potential limits to the restoration of woodlands on landfills. *Restoration Ecology* 6:280–289.
Robinson, G.R. and S.N. Handel. 1995. Woody plant roots fail to penetrate a clay-lined landfill. *Environmental Management* 19:57–64.
U.S. Environmental Protection Agency (USEPA). 1989. Final covers on hazardous waste landfills and surface impoundments. Environmental Protection Agency Report EPA/530/SW-89/047. Washington, D.C.
U.S. Environmental Protection Agency (USEPA). 2006. Revegetating landfills and waste containment areas fact sheet. Washington, D.C.: Environmental Protection Agency Publication EPA 542-F-06-001.
Vasey, M.C. 2012. Influence of the summer marine layer on maritime chaparral and implications for conservation policy in the California coastal zone. Ph.D. Dissertation: University of California, Santa Cruz.

Effects of Oak Woodland Restoration Treatments on Sapling Survival and Tree Recruitment of Oaks in an Upland Mesic Oak-dominated Forest

J. Stephen Brewer (University of Mississippi, Department of Biology, P.O. Box 1848, University, MS 38677, jbrewer@olemiss.edu).

Oak-dominated (*Quercus* spp.) woodlands, defined here as mixed woody and diverse herbaceous plant communities with > 70% tree canopy containing few non-oaks (see also Taft 1997), comprise a small fraction of the area in North America occupied prior to fire suppression. Historically, frequent low intensity fires maintained oak-dominated forests, woodlands, and savannas across the Midwest and interior South of the United States (Anderson and Bowles 1999, Fralish et al. 1999, Heikens 1999, Brewer 2001, Van Lear 2004, Ruffner and Groninger 2006). Fire exclusion in the 20th century enabled fire-sensitive hardwoods to colonize previously fire-maintained oak woodlands (Hart et al. 2008, Nowacki and Abrams 2008). These tree species produced a more closed canopy (> 90%) than the historically open, sparse canopies of oak woodlands and savannas (Bowles and McBride 1998), leading to widespread oak regeneration failure and losses of groundcover plant diversity (Abrams 1992, Bowles and McBride 1998). These diverse oak communities are rare ecosystems (Anderson and Bowles 1999) and are thought to occupy less than 0.02% of the area in North America they occupied before fire exclusion (Nuzzo 1986).

One challenging aspect of oak woodland management and restoration is identifying prescribed fire regimes that will effectively promote oak regeneration and maintain groundcover plant diversity. Effective methods for promoting oak regeneration involve opening the canopy sufficiently to foster growth of an existing oak seedling/sprout layer and then, when (or if) necessary, implementing fire in such a way as to reduce competition with non-oak saplings but not cause excessive oak sapling mortality (Loftis 1990, Kruger 1997, Brose et al. 1999, Albrecht and McCarthy 2006, Iverson et al. 2008, Cannon and Brewer 2013). It remains unclear, however, whether the fire regimes necessary to maximize oak regeneration are compatible with the maintenance of groundcover plant diversity in oak woodlands. To the extent that fire regimes that promote oak regeneration conflict with the maintenance of groundcover plant diversity, practitioners must either implement fire regimes that create a mosaic of oak regeneration patches interspersed with patches of diverse groundcover vegetation or they must identify fire regimes that forge a compromise between oak sapling survival and the maintenance of groundcover plant diversity.

This study examined the effects of frequent fires proven to promote groundcover plant diversity in a mesic oak-dominated system (Brewer and Menzel 2009, K.S. Spiegel and J.S. Brewer, University of Mississippi, unpubl. data) on the survival of established oak sapling recruits and on oak tree recruitment. I tested two hypotheses: 1) frequent (biennial) burning of an established sapling layer in persistent gaps reduces sapling densities, including those of upland oak species; and 2) frequent burning prevents recruitment of tree-sized individuals from saplings (oak and non-oak).

In 2003, I established an oak woodland restoration experiment at Strawberry Plains Audubon Center (SPAC) in the loess plains of north-central Mississippi, a region characterized by gently rolling hills with moderately fertile, mesic silt and sandy loams in the uplands and floodplains. The primary objectives of the restoration experiment (i.e., the reference model; *sensu* Clewell and Aronson 2013) were 1) to increase the abundance and diversity of open oak